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INVESTIGATIONS OF LUNAR MATERIALS

FINAL REPORT

February 1, 1973 to July 31, 1973

R.L. Fleischer and H.R. Hart, Jr.

Principal Investigator: R.L. Fleischer

Prepared under Contract No. NAS 9-11583

by

Physics and Electrical Engineering Laboratory
Corporate Research and Development
GENERAL ELECTRIC COMPANY
Schenectady, New York

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lyndon B. Johnson Space Center
Lunar Receiving Laboratory
Houston, Texas

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ABSTRACT

Since this report marks the end of a period of continuous NASA support that began in late 1967, we present here both a summary of the new results of the last six months since the last contract report and a brief overview of the accomplishments of the program over the six year period. Most of the work is presented in papers numbered 1 to 28 listed in Appendix I and Appendix II. Briefly, in the particle track work we have developed a series of dating techniques for learning about the surface history of soil and rock samples; studied quantitatively the surface behavior and history of diverse lunar rocks and soils, erosion rates, and deposition rates; and improved our knowledge of the incident heavy cosmic ray spectrum, which provides a prime tool for much of this work.

INVESTIGATIONS OF LUNAR MATERIALS

R. L. Fleischer and H. R. Hart, Jr.

1. SUMMARY OF LAST SIX MONTHS

In the period since the last contract report, work has progressed primarily by making use of the now well established phenomenon of shock erasure of tracks.[8, 13, 14, 16, 17, 25, 28] Since the crystals that have lost their tracks may accumulate more after the shock, the fresh tracks can be used to date the impact events.

Figure 1 illustrates erasure effects. It shows that within a ~1500 cm distance around a nuclear explosion of 5 Kiloton TNT equivalent most of the tracks are removed and that effects are observable to at least 4000 cm.[28]

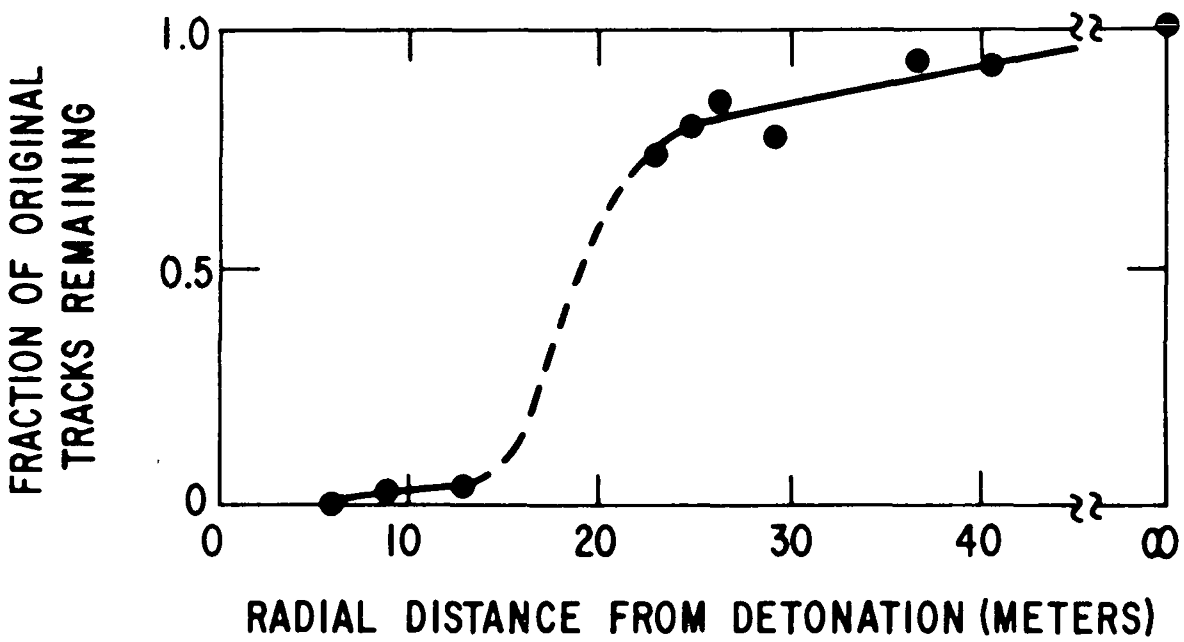

Figure 1 Track erasure in apatite shocked in the Hardhat nuclear explosion. Tracks are removed close to the detonation point.[28]

The existence of partial erasure that is implied by Fig. 1 was recognized in Apollo 15 rocks that we examined and then described in Ref. 16. We observed clear chemical-petrographic evidence of shock and wide variability in track densities. Since the particular samples (15058 and 15555) are not regarded as breccias, we inferred that the variability was introduced by shocks that followed long prior irradiations.

Extensive examinations of soils are reported in Ref. 17--an abstract for which is included here as Appendix IV. The central theme is that soil surface ages and total irradiations may be inferred from minimum and median track densities observed in individual soil samples, and that average deposition rates in core samples may be inferred by properly summing the exposures of individual layers. Most typically deposition rates range from 0.3 to 0.4 cm/ million years for four core sequences that we have been allotted.

A number of other samples have been studied, but not yet written up for publication. A brief description of the preliminary results follows.

Soil samples from the Station 9 trench at Van Serg Crater have been interpreted (as listed in Table I) as having been deposited in three steps at an average deposition rate of ~0.7 cm/million years. A single deposition for the whole 17 cm depth can be ruled out.

TABLE I

Station 9 Trench Soils - Van Serg Crater
[Three Step Deposition Model]

Sample	Depth [cm]	ρ (mm) 95% Conf. [10^6/cm^2]	Time At Surface [10^6 yr]
79221	2	4.7	11
79241	7	2.6	8
79261	17	0.58	5

Average deposition rate = 0.7 cm/my

Samples of the top cm of soil on a boulder at Camelot (75062 and 75061) gave exposures of 33(± 7) m.y. Track densities in 75081--from 5 cm deep--are similar and suggest that the material has experienced mixing after deposition.

Uranium concentrations have been measured in individual spherules of the Apollo 17 orange glass (74220) and in additional samples of the Apollo 15 green glass (15401). In contrast to the wide variability of 15401, 74220 has a nearly constant content of 70 (±20) p.p.b. Most of the variability in 15401 was found to occur in the low specific gravity (<2.6) fraction.

Apollo 16 rock 61016 contains a substantial cosmic ray track density that increases toward the surface in such a manner as to suggest that a recent 0.1 cm chip was lost (Fig. 2, left). With this assumption Fig. 2, right, indicates that a spectrum results that is compatible with the Surveyor 3 spectrum. The Surveyor 3 data has been reworked and clarified relative to our earlier presentation(3) and is given in Fig. 3. Two alternatives may be considered. One is that prior to the chip being lost the sample was exposed at the lunar surface for ~20 m.y. with negligible erosion. In the other alternative the irradiation was for ~40 m.y. and fine-scale erosion occurred at a rate of 0.6 Å/year. Rates of erosion significantly above 1 Å/year would be inconsistent with Fig. 2 (right).

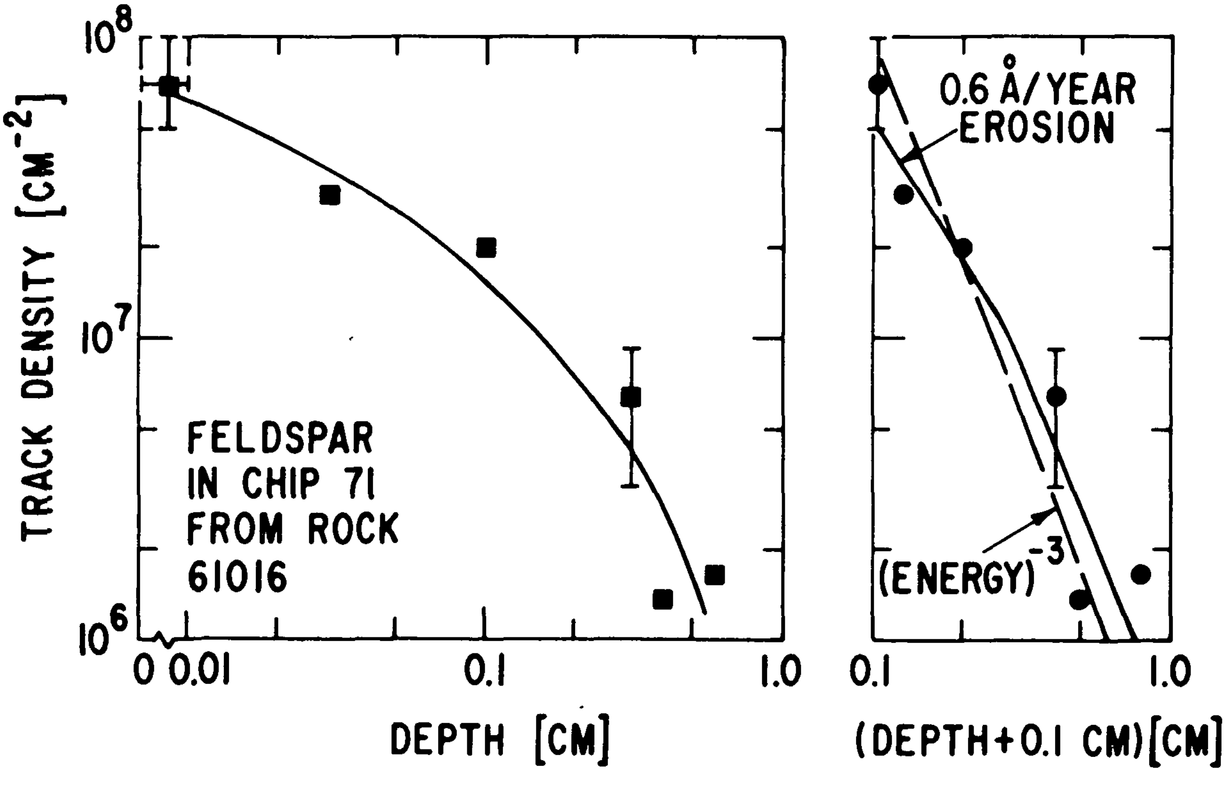

Figure 2 The unusual track density vs depth profile for rock 61016 (left) acquires a more conventional character if it is assumed, as at right, that a 1 mm chip was recently lost. Steady erosion occurred at no more than 1 Å/year.

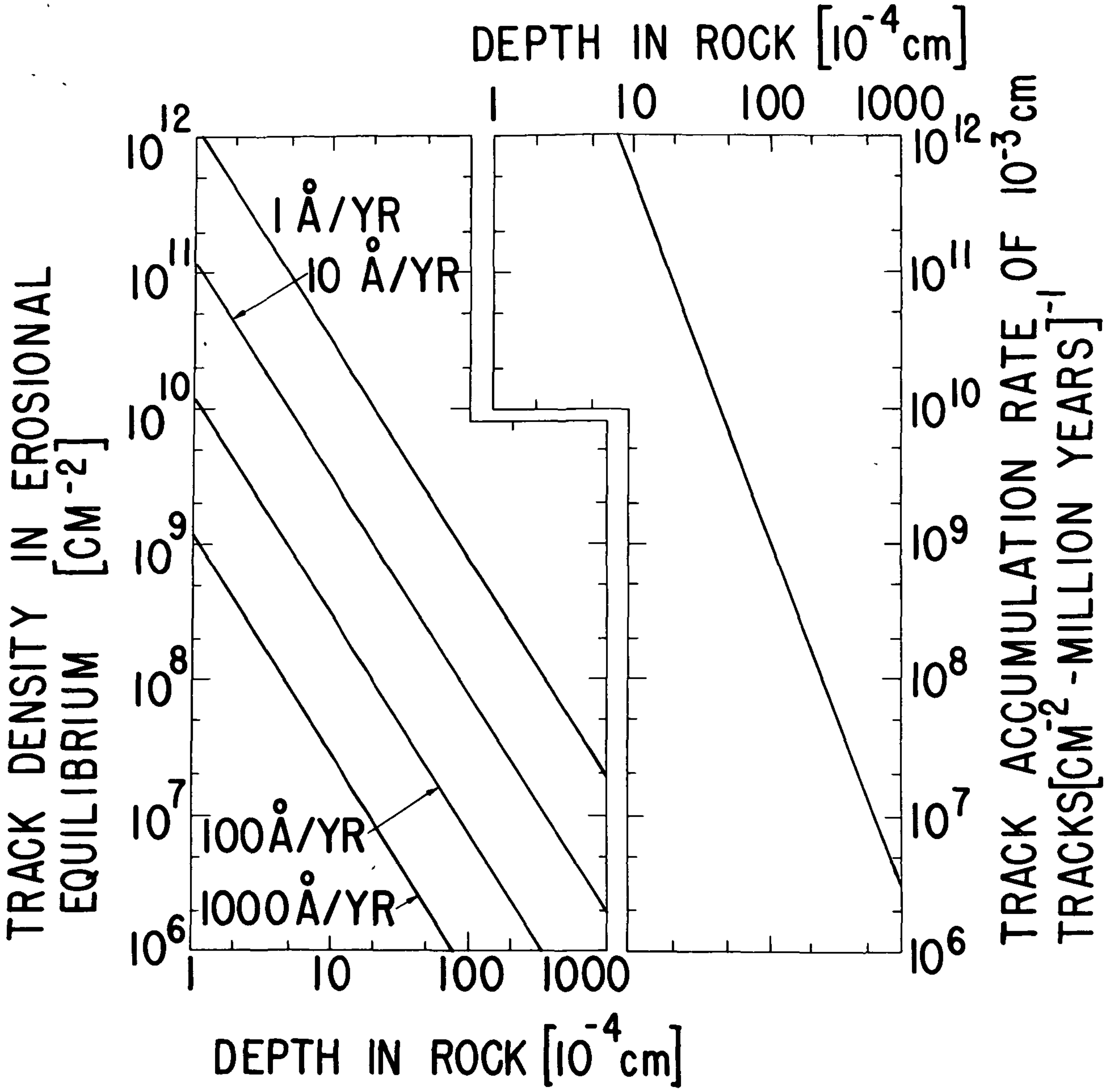

Figure 3 Track density vs depth as a function of erosion rate inferred from Surveyor 3 data.(3) The curve on the right gives the track accumulation rate in the absence of erosion. Points on the steady state curves on the left apply only as long as the track densities are significantly less than those obtained by multiplying the track production rate at the present depth by the total time of irradiation.

An interior sample (,35) of rock 61175 has a track density of $9.4 \times 10^6/cm^2$, which implies a cosmic ray exposure of 20 million years if it was exposed at the lunar surface, and a longer cosmic ray exposure if it was buried. A surface chip (23) was too severely shocked to give useful track results.

Attempts to observe cosmic ray tracks in the supposedly glass-lined pits in 79135,30 were unsuccessful because the linings were in fact highly poly-crystalline.

2. OVERVIEW OF THE GENERAL ELECTRIC LUNAR SAMPLE PREPARATION AND ANALYSIS WORK

The accomplishments of the track program over the last six years are listed in Tables II and III, which refer respectively to the preparation phase and the lunar materials examination phase of the work. These tables are referenced to the twenty-eight journal articles in which the work has been (or is being) reported. In addition six short papers (or extended abstracts) have appeared in the volumes entitled Lunar Science III, Lunar Science IV, and The Apollo 15 Samples.

TABLE II

Accomplishments of the Pre-lunar Studies (1967-1969)

dating of craters[18, 19]

search for extinct fission activity[22, 24, 26]

identification of distinct tektite fall[20]

handling of extra-terrestrial material[23]

evaluation of registration. particle identification, and thermal effects in tractor detectors[21, 27]

evaluation of shock effects on tracks[25, 28]

The preparation phase was characterized by studies of various processes that were thought to occur on the moon (cratering, impact effects, thermal effects) or of objects such as might be found on the moon (meteorites and tektites) or of particle registration and identification such as proved necessary for quantitatively dealing with cosmic ray tracks. In retrospect this work served well in its primary purpose as preparation and at the same time led us toward the discovery of the shock erasure phenomenon later in lunar samples. The work also uncovered a totally new and unexpected result -- the existence of two separate tektite falls in Australia.

TABLE III

Milestones in the General Electric Lunar Sample Program

1970	identification of cosmic ray, spallation recoil, and probable solar wind tracks (1, 2)
	ages of residence in top 15 cm measured from cosmic ray tracks (1, 2, 4, 5, 9, 11, 12, 16, 17)
	rough energy spectrum of heavy solar cosmic rays derived (2)
1971	ages of residence in top 100 cm measured from spallation recoil tracks (5)
	soil model constructed and documented to explain observed distribution of irradiations of soil grains (4, 6)
1971-73	improved heavy cosmic ray energy spectrum from Surveyor III (3)
	rock erosion rates derived (3)
1972	mechanical erasure of tracks recognized (8)
	erosion rates of brecias measured (9)
	soil layering histories measured including soil deposition rates (using newly recognized mechanical erasure effect) (13, 14, 17)
	soil with shortest surface exposure yet known identified (12)
1973	ubiquitous nature of shock effects documented (14, 16)
	quantitative soil exposure and deposition histories measured for a sizable group of Apollo 15, 16, and 17 samples, using mechanical erasure effects (17, and further work mentioned in section 1)

The lunar sample program progressed through a sequence first of identification of different varieties of tracks (spallation, cosmic ray, fission, solar wind), to the use of these tracks to date various process in lunar surface history (residence in top 0-1 mm, residence in top 15 cm, residence in top 200 cm, residence since last shocked), to the use of these dating methods to measure quantitatively the rates of lunar processes such as deposition, mass wastage, fine scale erosion, crater formation, ... The Surveyor 3 results[3] improved on earlier inferences[2] on the energy spectrum of low energy heavy solar nuclei and placed them on a firm footing. These results played a significant role in our ability to understand the erosion of rocks. The recognition of the shock erasure phenomenon has supplied a second major new tool that has shown considerable usefulness in the understanding of soils and is beginning to be shown to be relevant to understanding rock history.

ACKNOWLEDGMENT

We are deeply appreciative of the opportunity we have had to participate in the Apollo lunar materials program, starting at its inception and continuing through all of the lunar landings. The use of the preceious samples and the information they have yielded have made the last four years a unique period of scientific advance and have provided excitement not only for ourselves and the general scientific community but throughout the local community. We are pleased to give thanks to those in NASA who helped to make the lunar science program work and extend special thnaks to those who accepted on its own merits our original proposal for support of lunar work at an industrial laboratory.

APPENDIX I

List of Papers on Lunar Samples

1. R.L. Fleischer, E.L. Haines, R.E. Hanneman, H.R. Hart, Jr., J.S. Kasper, E. Lifshin, R.T. Woods, and P.B. Price, Particle Track, X-Ray, Thermal, and Mass Spectrometric Studies of Lunar Material from Apollo 11, Science 167, 568-571 (1970).

2. R.L. Fleischer, E.L. Haines, H.R. Hart, Jr., R.T. Woods, and G.M. Comstock, The Particle Track Record of the Sea of Tranquillity, Geochim et Cosmochim Acta, Apollo 11 Supplement 3, 2103-2120 (1970).

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6. G.M. Comstock, The Particle Track Record of the Lunar Surface, Proc. IAW Symp. 47, Newcastle, March 1971.

7. G.M. Comstock, R.L. Fleischer, and H.R. Hart, Jr., Particle Track Record of the Sea of Plenty, Earth and Planetary Sci. Let. 13, 407-409 (1972).

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11. G.M. Comstock, R.L. Fleischer, and H.R. Hart, Jr., The Particle Track Record of the Luna Missions, The Moon, 7, 76-83 (1973).

12. R.L. Fleischer and H.R. Hart, Jr., Particle Track Record of Apollo 15 Green Soil and Rock, Earth and Planetary Sciences Letters 18, 357-364 (1973); extended abstract in The Apollo 15 Lunar Samples, J.W. Chamberlain and C. Watkins (eds.), Lunar Sci. Inst., Houston, 1972 pp. 368-370.

13. R.L. Fleischer and H.R. Hart, Jr., Particle Track Record in Apollo 15 Deep Core from 54 to 80 cm Depths, Earth and Planetary Sciences Letters (1973); extended abstract in The Apollo 15 Lunar Samples, J.W. Chamberlain and C. Watkins (eds.) Lunar Sci. Inst., Houston, 1972 pp. 371-373.

14. R.L. Fleischer and H.R. Hart, Jr., Mechanical Erasure of Particle Tracks, a Tool for Lunar Microstratigraphic Chronology, J. Geophys. Res. (1973).

15. R.L. Fleischer and H.R. Hart, Jr., Tracks from Extinct Radioactivity, Ancient Cosmic Rays, and Calibration Ions, Nature 242, 104-105 (1973).

16. R.L. Fleischer, H.R. Hart, Jr., and W.R. Giard, Particle Track Record of Apollo 15: Shocked Crystalline Rocks, 4th Lunar Science Conf. (1973) (Supplement 4, Geochim. Cosmochim. Acta).

17. R.L. Fleischer, H.R. Hart, Jr., and W.R. Giard, Surface History of Lunar Soil and Soil Columns, Geochim. Cosmochim. Acta (1973).

APPENDIX II

List of Papers Written Under NASA Support Preparatory to Lunar Sample Availability

18. R.L. Fleischer, J.R.M. Viertl, and P.B. Price, Age of the Manicouagan and Clearwater Lakes Craters, Geochim, Cosmochim. Acta 33, 523-527 (1969).

19. R.L. Fleischer, P.B. Price, J.R.M. Viertl, and R.T. Woods, Ages of Darwin Glass, Macedon Glass, and Far Easter Tektites, Geochimica et Cosmochimica Acta 33, 1071-1074 (1969).

20. R.L. Fleischer, P.B. Price, and R.T. Woods, A Second Tektite Fall in Australia, Earth and Planetary Science Letters, 7, 51-52 (1969).

21. R.L. Fleischer, P.B. Price, and R.T. Woods, Nuclear Particle Track Identification in Inorganic Solids, Phys. Rev., 188, 563-567 (1969).

22. P.B. Price and R.L. Fleischer, Are Fission Tracks in Meteorites from Super-Heavy Elements? Phys. Letters 30B, 246-248 (1969).

23. R.L. Fleischer, E. Lifshin, P.B. Price, R.T. Woods, R.W. Carter, and E.L. Fireman, Schenectady Meteorite, Icarus, 12, 402-406 (1970).

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27. R.L. Fleischer and H.R. Hart, Jr., Fission Track Dating: Techniques and Problems, Proc. of Burg Wartenstein Conf. on Calibration of Hominoid Evolution [GE preprint #70C328], W.W. Bishop, J.A. Miller, and S. Cole (eds.), Scottish Academic Press, Edinburgh (1972), pp 135-170.

28. R.L. Fleischer, R.T. Woods, H.R. Hart, Jr., P.B. Price, and N.M. Short, Effect of Schock on Apatite and Sphere Crystals from the Hardhat and Sedan Underground Nuclear Explosions, submitted to J. Geophys. Res. (1973).

APPENDIX III

Particle Track Record of Apollo 15--Shocked Crystalline Rocks

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PARTICLE TRACK RECORD OF APOLLO 15--SHOCKED CRYSTALLINE ROCKS

by

R. L. Fleischer, H. R. Hart, Jr., and W. R. Giard
Physics and Electrical Engineering Laboratory

Report No. 73CRD143 April 1973

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SUMMARY

Cosmic ray track densities in two mare basalts, 15058 and 15555, are multivalued at each depth from the surface, and numerous indications of shock are present, suggesting that shock has lowered track densities in some crystals but not in others. From the minimum track densities, the maximum time since the last shock event is derived for each rock. In separate observations 15017, a black glass, has a surface age of ~14, 000 years derived from impact pits, but a solar flare record of only 1 year.

KEY WORDS

moon, particle tracks, cosmic rays

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RD-54 (10/70)

PARTICLE TRACK RECORD OF APOLLO 15--SHOCKED CRYSTALLINE ROCKS

R. L. Fleischer, H. R. Hart, Jr., and W. R. Giard

INTRODUCTION

The record left by heavy cosmic ray nuclei in Apollo 15 rocks reveals complicated but interesting surface histories. We report here observations on crystalline igneous rocks, breccias, and a black glass shell displaying prominent impact pits. Our earlier observations of igneous rocks showed smooth variations of the track density from solar and galactic cosmic rays that decreased monotonically inward with very little scatter (FLEISCHER et al., 1970, 1971a) as was predicted for simple objects that accumulate and retain tracks over some time period (FLEISCHER et al., 1967a). On the other hand, breccias often give widely varied track densities at each depth, indicating that many of the grains making up these rocks received cosmic ray bombardment prior to their being compacted into rock, and that many of the tracks from the pre-irradiation survived the impacts which made the breccias (HART et al., 1972). In the present work we find a puzzle--a similar type of scatter can be seen in igneous rocks, which by their nature could not have had a pre-irradiation of the grains separately

EXPERIMENTAL PROCEDURES

Except where specifically noted, groups of grains were removed from specified locations in the rock samples reported here, mounted in epoxy, and polished prior to etching to reveal natural tracks. The procedures for mounting and polishing have been described in detail in a series of papers (FLEISCHER et al., 1970, 1971a; FLEISCHER and HART, 1973b). Reported track densities are increased relative to the raw data by dividing by 1.0, 0.7, 0.5, and 0.2 for feldspar, pyroxene, olivine, and glass, respectively, to allow for the differing etching and registration efficiencies of these detectors. Track densities reported are generally for tracks of length greater than 1 5μ. Shorter tracks were placed in a separate category that will be discussed whenever considered. The "95% confidence minimum track density" is obtained by considering the feldspar or pyroxene with the lowest track density at a particular location in a rock and raising its track density by two standard deviations determined from the number of tracks counted in that crystal. Unless specific annealing data are available, lunar olivine and glass are normally excluded because of potential track fading problems.

ANALYSIS PROCEDURES

Most of the tracks of interest here are heavy cosmic rays of charge ~26, the so-called iron-group nuclei. If a sample has been buried at a known depth in a material, a knowledge of the flux of these nuclei plus the track density accumulated at that position allows the near surface exposure time to be computed.

We will make use of our previous observation that shock events commonly fragment and erase tracks (FLEISCHER et al., 1972; FLEISCHER and HART, 1973a) so that if a rock is shocked, some of the crystals will start recording tracks with a newly cleaned slate. The minimum track density among a group of grains identifies the one with the most recently and/or most completely erased tracks and allows the shock event to be dated. Similarly, finding the minimum track density at a known depth in a sample allows the last track-erasing shock to be dated Most generally the age so found will be an upper limit, since the search for the most recently shocked material in which all tracks were erased may not have been successful One may have found a crystal that was shocked in an earlier impact or in which only a fraction of the pre-existing tracks were erased.

INFERRING SURFACE AGES

In using cosmic ray track densities to estimate rock residence times close to the lunar surface we will utilize as appropriate either the track production relation given in Fig. 1, which was computed for a grain of average orientation buried in a semi-infinite rock of overall specific gravity 3.4 or the calculations of FLEISCHER et al., (1967a) for spherical bodies of various sizes. The track production rate of Fig 1 is based on the calculation of COMSTOCK (1972) His production rate has been scaled up by a factor of two so as to utilize the same cosmic ray flux as was assumed by FLEISCHER et al., (1967a, b) for the interior of meteorites; this doubling is, as noted by FLEISCHER and HART (1973a), consistent with recent calibration results for heavy ions. The steeply descending portion of the curve at depths of less than ~0.3 cm corresponds to solar flare particles Since the Surveyor 3 observations used (CROZAZ and WALKER, 1971; FLEISCHER et al., 1971b; PRICE et al., 1971) were made over less than a full solar cycle, the long term average flux is not known accurately Therefore, ages inferred from grains buried by less than 0.3 cm will be uncertain to roughly a factor of two

RESULTS

Igneous Rock 15058

This rock has been classified as a type I mare basalt (BROWN et al., 1972). Figure 2 indicates the location of our column and chip, Fig. 3 gives the densities of cosmic ray tracks in various minerals as a function of position, and Fig. 4 shows the density of short (≤ 1 1/2μ) tracks in pyroxenes. Figure 3 has two interesting and obvious features. The first is the wide range of track densities at each depth. Even if only the most retentive materials, the feldspar and pyroxenes, are considered the track densities vary

Manuscript received April 25, 1973

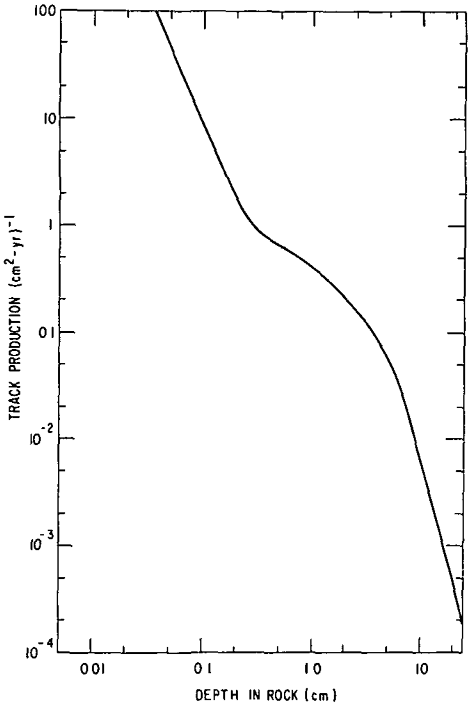

Fig. 1 Calculated average track production rate in lunar rock of density 3.4 g/cc. The rate given here is twice that of COMSTOCK (1972) as discussed in the text

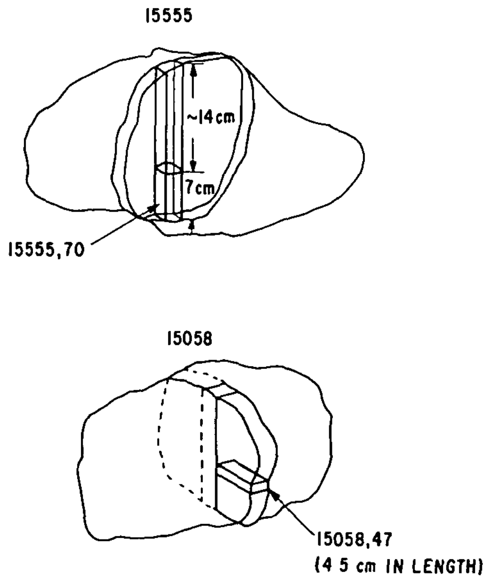

Fig. 2 Positions of the samples studied from rocks 15058 and 15555.

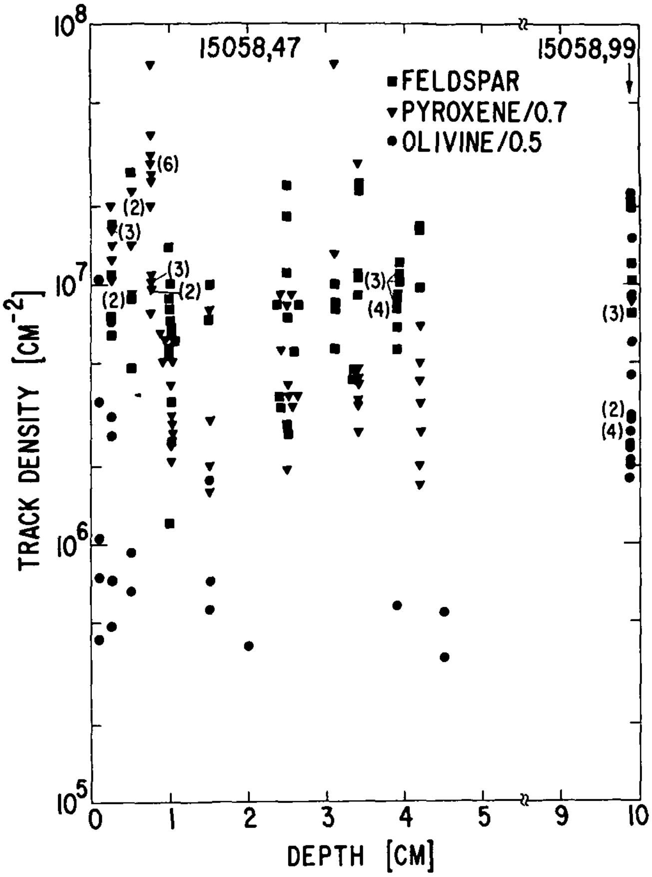

Fig. 3 Track densities observed in individual crystals of three different minerals of 15058, 47 and 15058, 99. The pyroxenes show evidence of shock.

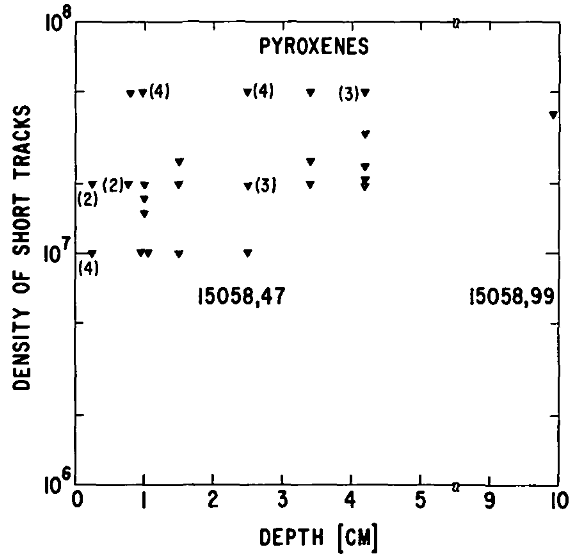

Fig. 4 Density of short tracks (≤ 1.5μ in length) in pyroxenes from 15058

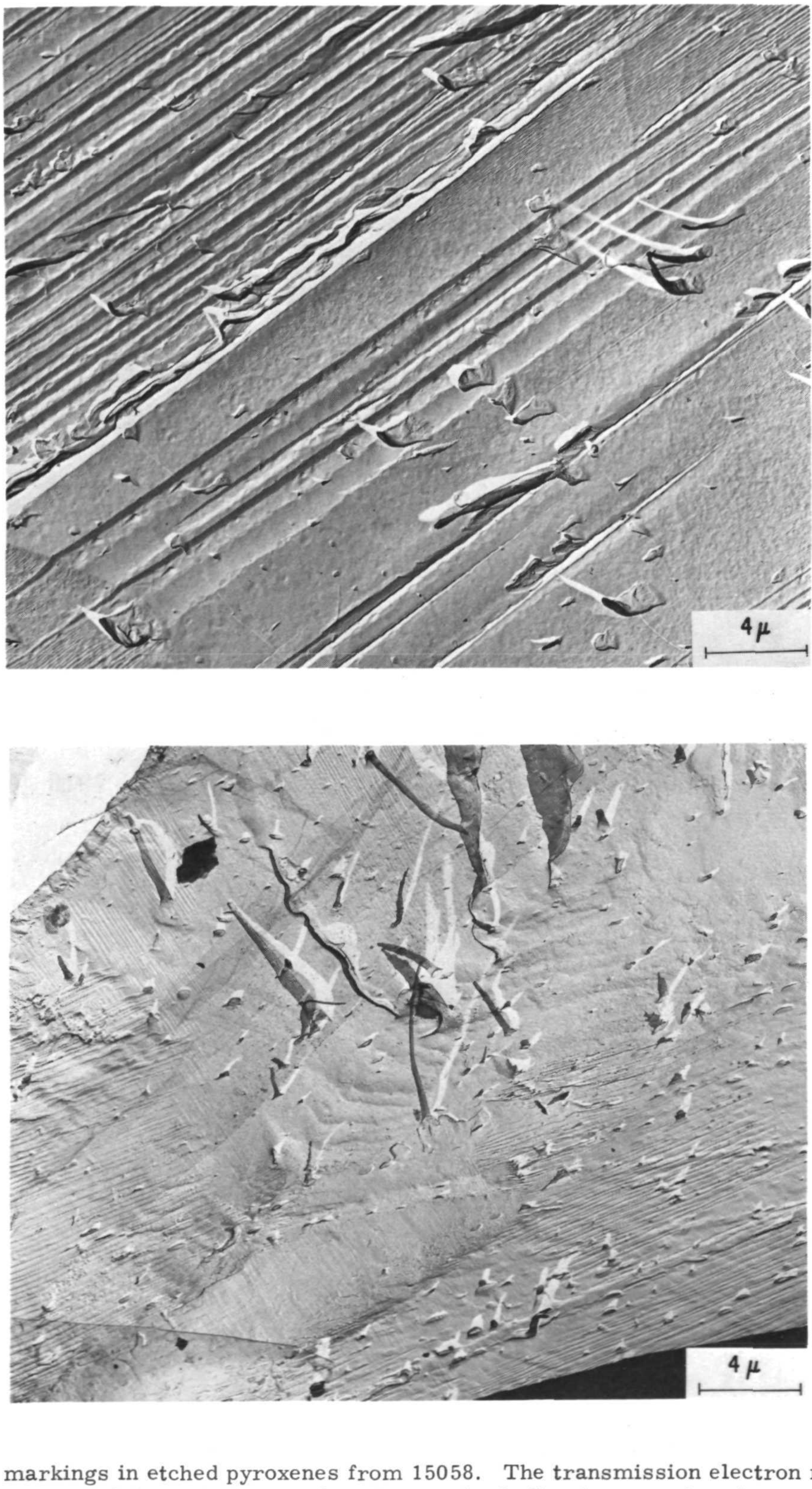

Fig. 5 Deformation markings in etched pyroxenes from 15058. The transmission electron micrographs are made of shadowed replicas of the etched crystals. Top: mixed slip plane spacings in a grain from a depth of 7 mm; and bottom: duplex slip in a crystal from within 2.5 mm of the surface.

by a factor of ten at most depths. The second striking feature is that the olivines are consistently lower than the other minerals in spite of the fact that they are corrected for their typical lesser sensitivity. BHANDARI et al., (1972) report a smoothed fit to their data which is consistent with our data at 4.2 cm, where our samples join, but they do not indicate minimum or maximum track densities

Unless the classification of this rock is wrong, the tracks we observe are not inherited tracks from previous existence of the crystals as separate soil grains, and hence the tracks must have been altered by thermal (FLEISCHER et al., 1965) or mechanical effects (FLEISCHER et al., 1972). We believe that both have probably occurred

Clear evidence of mechanical effects has been obtained, as shown by the electron micrographs (Fig 5) of two etched pyroxenes from 15058: one (top print) with a mixture of coarse and fine deformation markings and the other print (bottom) with duplex slip (deformation on two distinct sets of crystal planes). Twenty-one of 80 pyroxenes examined optically showed effects characteristic of deformation (FLEISCHER and HART, 1973a)--oriented tracks, deformation markings, or both; and 20 of 21 replicas of pyroxenes that were examined with the transmission electron microscope displayed deformation markings.

When deformation has erased tracks by dividing them into short, unresolvable segments, the long tracks that have accumulated after the deformation should allow the time of deformation to be measured (FLEISCHER et al., 1972). If as in this case some of the grains have apparently not had their tracks totally erased, the minimum track densities become the best approximation to the post deformation track accumulation. Accordingly, in Fig. 6 we have plotted the minimum track densities for each mineral type at each depth, and curves defining the envelope of the lower boundary for olivine and for feldspars plus pyroxenes. The fact that the olivines are low relative to the other minerals is consistent with their higher sensitivity to thermal effects. The near surface lowering also suggests that some brief but unidentified surface heating might have played a role in reducing the track densities in the olivines.

Using the minimum track density of $1.7 \times 10^6/\text{cm}^2$ at 1 cm depth we infer an age of not more than 7 million years since this rock was last shocked.

The short tracks could either be proton-induced spallation recoil tracks or fragmented cosmic ray tracks. The results unfortunately are compatible with there being no variation with position or with a factor of 3 or 4 increase with depth from 0 to 4 cm, so that it is not possible to decide on the basis of the depth variation whether these are spallation tracks or not. If they are from spallation, the median value of $\sim 2 \times 10^7/\text{cm}^2$ would imply a proton exposure 1.1×10^{16} protons/cm^2 or a near surface age of a few 100 m.y. (FLEISCHER et al., 1971a). Regardless of spallation

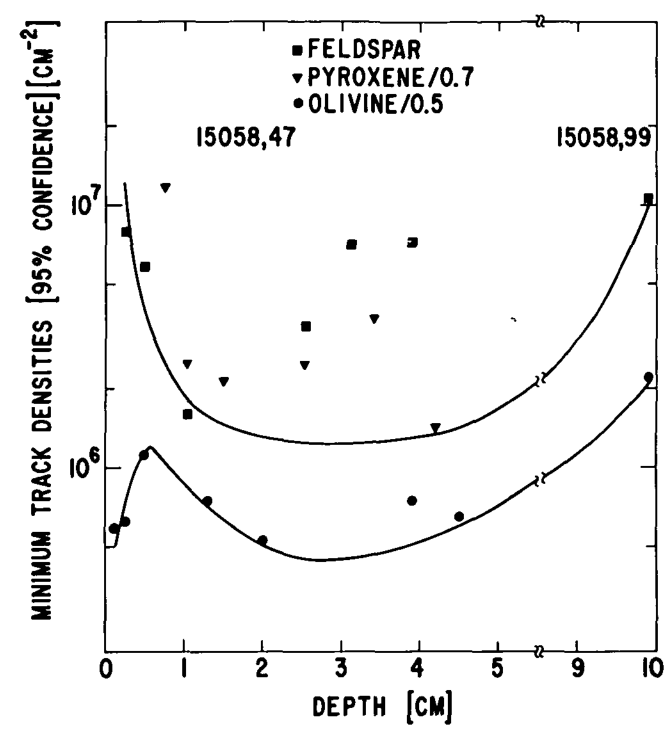

Fig. 6 Minimum track densities (95% confidence) at each position sampled in 15058. Curves show the smoothed lower limits for feldspars plus pyroxenes and for olivines.

tracks the maximum cosmic ray track densities of $\sim 3 \times 10^7/\text{cm}^2$ at 3 cm depth in the sample would imply ~1000 m.y. buried beneath 10 cm of soil, or a few 100 m.y. at a lesser depth. In short, a long near-surface prehistory is implied prior to the track erasing event $\lesssim$ 7 m.y. ago.

Rock 15555

This largest Apollo 15 rock is another mare basalt with somewhat similar properties to 15058, as Fig 7 indicates for the sample sketched in Fig. 2. Both median and minimum track densities are plotted Again, deformation markings are observed in the pyroxenes. As for 15058 the median values scatter rather widely, but are consistent with a slight increase in track density from the bottom surface toward the center of the rock. The track density of 2×10^6 at 1 cm from the bottom surface indicates that surface has been exposed to space less than 5 m.y. since the last track erasure. Because this same position is 14 cm from the top of the rock, it can be used to give a maximum time that the rock could have been in its present position since it was last shocked. This time, 900 m.y. is only an upper limit and not the true surface age since BHANDARI et al., (1972) report track densities as low as $4 \times 10^6/\text{cm}^2$ at the center of the rock.

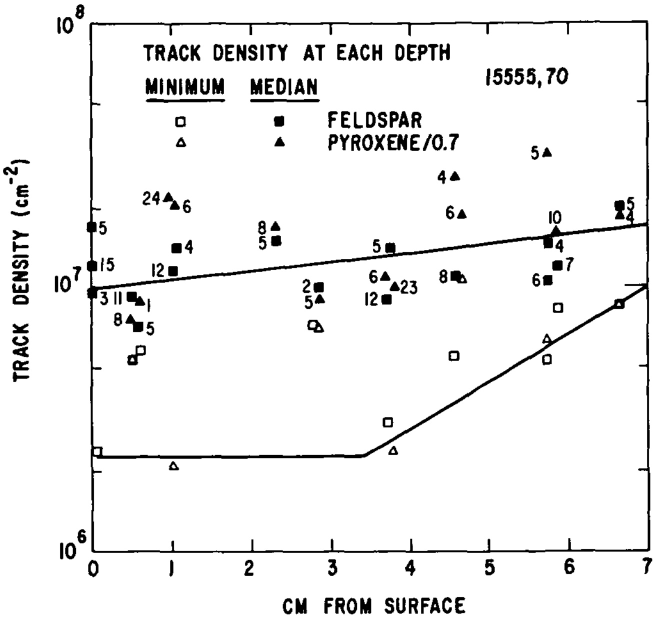

Fig. 7 Minimum (95% confidence) and median track densities at each position sampled in mare basalt 15555. Numbers adjacent to points indicate the number of separate measurements from which the medians were determined.

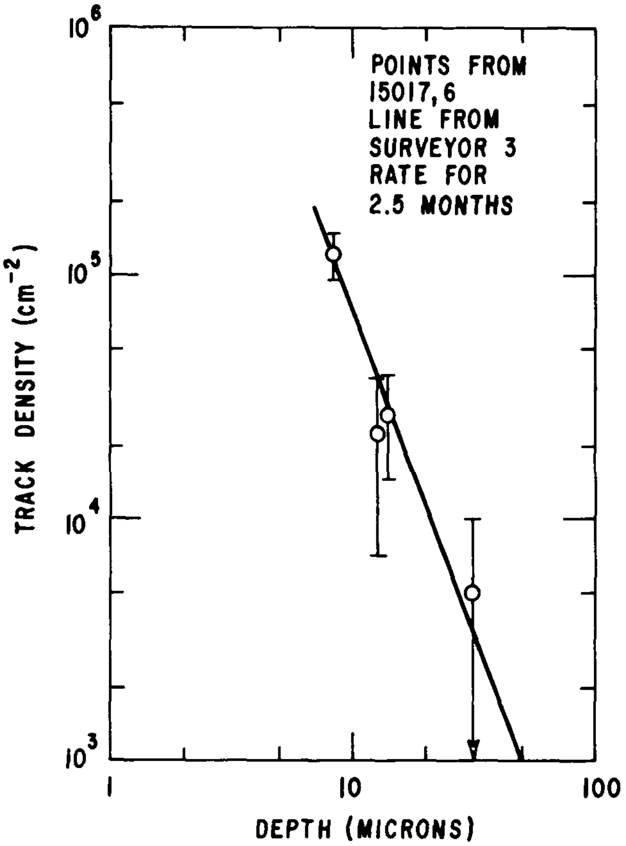

Fig. 8 Track density gradient observed in glass shell 15017, which was exposed to micrometeorites for >10,000 years. The slope is consistent with the Surveyor 3 solar flare energy spectrum determined from Surveyor 3 (FLEISCHER et al., 1971b) using the fluence for a one-year exposure, a discrepancy that is explained by track fading.

15505: Exposure Time to Solar Cosmic Rays

This sample, a breccia taken from station 9 near a crater, contained a minimum track density in pyroxene of $2 \times 10^6/cm^2$ at 1.5 mm below the surface. From a track production rate of $3.5/cm^2$-yr we compute a surface age of ≤ 600,000 years for this surface with 95% confidence.

15017 and Impact Pit Counting

Sample 15017,6 is a vesicular, black, glass shell of varying thickness (1 to 5 mm) and irregular composition from point to point (FABEL et al., 1972). Its exterior displays a low density of classic impact pits with interior craters surrounded by spall zones. The area of approximately 1 cm^2 has one pit of crater diameter >200μ, 3 of >100μ, and 6 of >50μ, as viewed at 30X in a stereo microscope. From the flux of hypervelocity micrometeorites inferred by HARTUNG et al., (1973), a surface exposure of ~14,000 years is implied.

In an attempt to obtain a track age to compare with this impact age, we examined a 1-mm-thick exterior fragment and performed a limited number of heating experiments to assess track fading. Track counts were made on the exterior face after two different etching times to observe tracks of cone angle 55° (±5°) ending near 8.5μ and 13μ depths in the glass, and an in-profile view revealed tracks at 14μ and 31μ beneath the original surface. In Fig. 8 these limited data are plotted along with a curve that represents the density vs depth relation expected if the sample were irradiated by cosmic rays for 2 1/2 months at the flux observed between the landing of Surveyor 3 and that of the Apollo 12 mission (FLEISCHER et al., 1971b).

The discrepancy of a factor of 10^5 between the impact age and this apparent surface age is explained as thermal track fading. Using Cf-252 fission tracks we find that a 50-minute anneal at 230°C removes all of the tracks from most of the glass, with tracks being retained in some less rapidly etching portions (of, therefore, different composition from the majority). This fading is more rapid than that in the black glaze on rock 12017 where we inferred (FLEISCHER et al., 1971a) that fission tracks would be stable for ~500 yr on the lunar surface. Since cosmic ray tracks would be less tenatiously retained (MAURETTE et al., 1970; Price et al., 1973), a retention time ~ a year or less is consistent with the data.

If we consider the cosmic ray fluxes up to the time of the Apollo 15 mission, we find that the fluence of protons over the 2 1/2 months just prior to the mission is much too low to provide the density of heavy particles we observed, assuming the iron/hydrogen ratio of $\sim 10^{-4}$ that we observed at ~ 1 MeV/amu (FLEISCHER and HART, 1973c). Because the sun was more active prior to that period, we can however, explain the observed dose if we assume that the glass retained the heavy particle tracks formed over a ~ 1 year time prior to its collection on Apollo 15.

CONCLUSIONS

We have shown that, in two mare basalts, track densities are lowered by shock, by different amounts in different crystals. From the minimum track densities upper limits can be derived for the cosmic ray exposure times since the last shock event

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APPENDIX IV

Abstract of Paper to Appear in Geochimica et Cosmochimica Acta

Surface History of Lunar Soil and Soil Columns

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Abstract

Measurements of cosmic ray track densities are presented for soil samplease from Apollo 15, 16, and 17. Median track densities are used to infer total effective exposure times within ~15 cm of the lunar surface. Minimum track densities are used to derive the time of the last impact-produced rearrangement of soil grains. For samples from near various craters ages are derived of 40 m.y. for St. George, 6 (± 3) m.y. for S. Ray, 25-90 m.y. for Plum, and 20 to 35 m.y. for Shorty. The material of 15003, the Apollo 15 deep core at depths of 120 to 160 cm is inferred to have been deposited at an average rate of ≥ 0.35 cm/m.y. The Apollo 16 core at 41-47 cm depths, 60007, appears to be well mixed and was covered up by deposition at >0.3 cm/m.y. for the next few m.y. after its deposition.